Annual Report
September, 1994
Methods Development for an Unenclosed Mesoscale Iron Enrichment
OCE N00014-94-1-0125
Johnson/Coale

GOALS

The long-term goals of this work are to test the hypothesis that metals, especially iron, regulate rates of primary production in High Nitrate, Low Chlorophyll (HNLC) areas of the ocean. An important corollary of this hypothesis is that it might be feasible to regulate productivity in small patches in the open ocean by addition of small amounts of iron. The ability to produce "mini-blooms" would be an extremely valuable experimental tool for the study of ocean biogeochemistry.

OBJECTIVES

The primary objective of the work undertaken in 1993 was to perform the first mesoscale (64 km^2) iron enrichment experiment in the open ocean. We also conducted a study of trace metal distributions downstream of the Galapagos islands. The area downstream of the Islands has elevated chlorophyll concentrations. We hypothesized this to be a natural analog of an open ocean iron enrichment experiment in which the iron was derived from the Islands.

APPROACH

The implementation of a mesoscale iron enrichment experiment, originally conceived by John Martin, required that considerable physical, chemical, and logistical obstacles be overcome. A series of experiments were performed to assess the feasibility of performing an open ocean iron fertilization experiment. These experiments indicated that it was feasible to perform an open ocean iron addition experiment. The first fertilization experiment was then conducted in October/November 1993 with a team of scientists from across the US and England. The fertilization experiment was immediately followed by the study of the Galapagos Plume.

TASKS COMPLETED

In previous studies, enrichment experiments were performed to determine which form would be most biologically available, cost effective and simulate the chemical form of atmospherically derived iron. Under this project, physical and chemical models were used to predict the speciation, solubility, and the final concentration of iron in surface waters injected with acidic iron sulfate. These models were developed in collaboration with Dr. Stephane Blain (University of Brest, France) during his three month visit to Moss Landing Marine Laboratories. Collaborative discussions with Drs. Tim Stanton and Andrew Watson (Navy Post Graduate School, Monterey, CA and Plymouth Marine Lab, UK respectively) resulted in a deployment strategy utilizing a lagrangian reference buoy about which the experiment would be carried out, and the results monitored. A system was designed to deliver regulated amounts of iron into the

SAN JOSE STATE UNIVERSITY FOUNDATION

September 27, 1994

Scientific Officer Code: 323C
Dr. Edward J. Green
Office of Naval Research
Ballston Tower One
800 N. Quincy Street
Arlington, VA 22217-5000

RE: Grant No. N00014-94-1-0125 - "Method Development for an Unenclosed Mesoscale Iron Enrichment"

Dear Dr. Green,

Enclosed is the original and two (2) copies of Moss Landing Marine Laboratories' annual progress report for the period October 1, 1993 to September 30, 1994.

If you have any questions, please call me at (408) 924-1435.

Thank you.

Bill Yabumoto
Contracts & Grants Analyst

Account No. 21-1509-0494

cc: ACO - N63375 (1)
Director, Naval Research Lab - Code 2627 (1)
Defense Technical Information Center (2)

ships wake along with an inert tracer (sulfur hexafluoride). Utilizing the R/V Sproul, a trial injection off the California Coast in which 800 liters of a 0.5 M $FeSO_4$ was introduced into the ship's wake over a 1.5 km^2 area, was used to test these predictions. Iron concentrations in this small scale patch were determined continually during the experiment using a shipboard colorimetric method, as the ship steamed in transects through the enriched patch. These preliminary results indicated excellent spatial agreement with model predictions and final concentrations which were consistent with the chemical model.

This equipment and strategy was then used to perform an open ocean fertilization experiment in HNLC waters south of the Galapagos Islands. The mixed layer (30 m) iron concentration in a 64 km^2 patch was raised from ca. <0.1 nM to a mean value of 3.5 nM by adding 500 kg iron to the mixed layer. This was sufficient iron to cause complete depletion of the available major nutrients (nitrate, phosphate and silicate). Chemical and biological properties of the patch were tracked for 9 days. A survey of metal distributions in the waters upstream and downstream of the Galapagos Islands was then conducted. Shipboard measurements of nutrients, oxygen and chlorophyll were performed on both cruises. Trace metals samples, particulate organic carbon samples, dissolved organic carbon samples and plankton species samples were collected on both legs of the cruise and are now being processed in the laboratory.

To date we have competed analyses of all particulate trace metal samples representing two size fractions ($.4\mu < x < 5\mu$ and $> 5\mu$) for Fe, Cd, Co, Cu, Ni, Pb, Zn and Al. All dissolved metals for the IronEx leg have been analyzed and dissolved analyses of samples from the PlumEx leg are continuing. Analyses of samples for POC, DOC and species composition are underway.

ACCOMPLISHMENTS

The first iron enrichment experiment was a major success. Addition of iron to a 64 km^2 patch produced increases in chlorophyll concentration and primary production rates that were 3 fold elevated over background values. We were able to track this patch for 9 days before returning to port. These results demonstrate that iron does regulate biological rates in HNLC areas of the ocean. They also clearly indicate the feasibility of performing controlled experiments on open ocean ecosystems for significant periods of time. It is clear, however, that the ecosystem in the fertilized patch did not behave similarly to that observed in containers on board ship. This difference has been attributed to the short residence time of iron in the patch, whereas in bottles, there is no removal of iron from the system.

We are continuing analysis of samples, planning the next IronEx experiment (May-June of '95) and working up the results of our last field effort. Due to the interest in the experiment and the untimely death of John Martin, Kenneth Coale has been asked to act as guest editor of a special issue of Deep-Sea Research honoring John Martin and focusing on the results of the IronEx and PlumEx cruises. Proposed submissions for this issue are appended at the end of this report.

Papers Published

Martin, J .H. and S. E. Fitzwater. 1992. Dissolved organic carbon in the Atlantic, Southern and Pacific Oceans. NATURE 356:699-700.

Martin, J.H. 1991. Iron as a limiting factor in oceanic productivity, pp. 123-137. In: P. Falkowski and A.D. Woodhead (eds.). Primary Productivity and Biogeochemical Cycles in the Sea. Plenum Press, NY.

Bender, M., H. Ducklow, J. Kiddon, J. Marra and J. Martin. 1992. The carbon balance during the 1989 spring bloom in the North Atlantic Ocean, 47°N, 20° W. Deep-Sea Res., 39:1707-1726.

J. H. Martin, K. H. Coale, K. S. Johnson, S. E. Fitzwater, R. M. Gordon, S. J. Tanner, C. N. Hunter, V. A. Elrod, J. L. Nowicki, T. L. Coley, R. T. Barber, S. Lindley, A. J. Watson, K. Van Scoy, C. S. Law, M. I. Liddicoat, R. Ling, T. Stanton, J. Stockel, C. Collins, A. Anderson, R. Bidigare, M. Ondrusek, M. Latasa, F. J. Millero, K. Lee, W. Yao, J. Z. Zhang, G. Friederich, C. Sakamoto, F. Chavez, K. Buck, Z. Kolber, R. Greene, P. Falkowski, S. W. Chisholm, F. Hoge, R. Swift, J. Yungel, S. Turner, P. Nightingale, A. Hatton, P. Liss, N. W. Tindale. Testing the Iron Hypothesis in Ecosystems of the Equatorial Pacific Ocean. Nature, vol 371, no. 6493, pp 123-129, 1994.

Kolber, Z. S., R. T. Barber, K. H. Coale, S. E. Fitzwater, R. M. Greene, K. S. Johnson, S. Lindley and P. G. Falkowski. Iron Limitation of Phytoplankton Photosynthesis in the Equatorial Pacific Ocean. Nature, Vol. 371, No. 6493, p 145-148, 1994.

Watson, A., C. S. Law, K. A. Van Scoy, F. J. Millero, W. Yao, G. E. Friederich, M. I. Liddicoat, R. H. Wanninkhof, R. T. Barber, and K. H. Coale. Minimal effect of iron fertilization of sea-surface carbon dioxide concentrations. Nature, Vol. 371, No. 6493, p 143-145, 1994.

Papers in Press or Submitted

Martin, J.H., S.E. Fitzwater, R.M. Gordon, N.W. Tindale, M.W. Peacock and R.A. Duce. 1992. Atmospheric iron stimulates phytoplankton growth in the equatorial Pacific.

Fitzwater, S. E. and J. H. Martin. Notes on the JGOFS North Atlantic bloom experiment DOC-HTCO Intercalibration. A background paper for the DOC/DON workshop, Seattle July 1991. Mar. Chem.

Fitzwater, S. E., K. H. Coale, R. M. Gordon, K. S. Johnson and M. E. Ondrusek. Iron deficiency and phytoplankton growth in the Equatorial Pacific. Submitted, JGOFS EQ-PAC Special Issue, Deep-Sea Research.

Gordon, R. M., K. H. Coale, K. S. Johnson and S. E. Fitzwater. Iron distribution in

the Equatorial Pacific: Implications for new production. Submitted, JGOFS EQ-PAC Special Issue, Deep-Sea Research.

Coale, K. H., S. E. Fitzwater, R. M. Gordon and K. S. Johnson. Iron Limits New Production and Community Growth in the Equatorial Pacific Ocean. Science, Submitted.

Invited conference presentations

Johnson, K. S. Invited speaker, 1993 Gordon Research Conference on Chemical Oceanography, "The Galapagos Iron Fertilization Experiment", August 16-20, Meriden, NH.

Johnson, K. S. Autonomous Bio-optical Ocean Observing Systems, April 6-10, 1992, Monterey, CA. Invited session chair for Sensor Systems. Invited talk, "Chemical analyzers and sensors for deep-sea moorings".

Coale, K. H. Invited speaker, Asian Dust Symposium, University of Rhode Island, June, 1992. R. Arimoto convenor, The role of Atmospherically derived trace metals on phytoplankton productivity: An emphasis on iron.

Johnson, K. S. Invited speaker, USC SeaGrant Program Review, March 17, 1992, Los Angeles, CA. "Metal fluxes from sediments at the Whites Point Sewage Outfall".

Coale, K. H. Invited speaker and participant. FeLine II IGAC/MAGE-EqPac. Studies of the Equatorial Pacific at 140°W. Proceedings Report EqPac Data and Science Workshop #1. NOAA/PMEL Seattle WA, July 12-16, 1993

Coale, K. H. The Iron Hypothesis: Mesoscale Enrichment in the Equatorial Pacific. Invited presentation, Global Biogeochemical Cycles Seminar Series Co-Sponsored by the Center for Analysis of Environmental Change and the Department of Chemical Oceanography, Oregon State University, Corvallis, April 21, 1994.

Coale, K. H. and the IronEx Group. Mesoscale Iron Enrichment and Galapagos Plume Studies in the Equatorial Pacific. 1994. Iron Speciation and its Biological Availability in Seawater: A Workshop. Bermuda Biological Station for Research, May 1-5, 1994.

Johnson, K. S., K. H. Coale, S. Fitzwater, V. A. Elrod, J. Nowicki, M. Gordon, T. Coley and C. Hunter. Iron Photochemistry and Analytical Chemistry. 1994. Iron Speciation and its Biological Availability in Seawater: A Workshop. Bermuda Biological Station for Research, May 1-5, 1994.

Barber, R., S. Lindley, R. Bidigare, M. Latasa, M. Ondrusek, K. Buck, F. Chavez, S.

Chisholm, K. Coale, S. Fitzwater, M. Gordon, C. Hunter, K. Johnson, S. Tanner, A. Watson, C. Law, K. Van Scoy and M. I. Liddicoat. The In Situ Phytoplankton Response to Natural and Experimental Iron Enrichment. 1994. Iron Speciation and its Biological Availability in Seawater: A Workshop. Bermuda Biological Station for Research, May 1-5, 1994.

Coale, K., M. Gordon and S. Fitzwater. Iron Limitation on Primary/New Production and Biomass in the Equatorial Pacific. Contribution as invited participant to the working groups on Iron and Grazing/New Production and Export, EqPac Data Synthesis and Overview Workshop. Scotsdale Arizona, June 11-21, 1994.

Coale, K. and the IronEx Group. Iron Enrichment of Equatorial Pacific Waters: Mesoscale Test of the Iron Hypothesis. Invited presentation, The Oceanography Society, July 19-22, 1994, Honolulu, Hawaii.

Contributed conference presentations

Elrod, V. A., K. H. Coale, T. L. Coley, J. L. Nowicki and K. S. Johnson. Iron Enrichment Experiments in the Equatorial Pacific: The Role of the Form of Added Iron. EOS, 73, 82, 1992.

Coale, K. et al. and the Ironex Group. 1994. The Martin iron experiments: Overview and iron chemistry. EOS, 75, 134.

Fitzwater, S., K. Coale, S. Blain, T. Coley, C. Hunter, and K. Johnson. 1994. The design and implementation of a mesoscale iron enrichment experiment in the Equatorial Pacific. EOS, 75, 150.

Gordon, M., K. Coale, and K. Johnson. 1994. Iron distributions in the Equatorial Pacific: Implications for new production. EOS, 75, 114.

Hoge, F. and The IronEx Group. 1994. Distinct Fluorescence Signatures of an Iron-Enriched Phytoplankton Community in the Eastern Equatorial Pacific Ocean: A Comparison with Contiguous Naturally-Occurring Patches. EOS, 75, 134.

Hunter, C., M. Gordon, S. Fitzwater and K. Johnson. 1994. A rosette/winch system for the collection of trace metal clean, large volume discrete seawater samples. EOS, 75, 150.

The Ironex Group and R. Barber. 1994. The transient addition experiment: The phytoplankton response. EOS, 75, 134.

Kolber, Z., and the Ironex Group. 1994. Biophysical response of marine phytoplankton to *in situ* iron enrichment as measured by FRR (Fast Repetition Rate) Fluorescence. EOS, 75, 114.

Millero, F., and the Ironex Group. 1994. The carbonate system in the waters near the Galapagos Islands. EOS, 75, 114.

Sakamoto, C. M. and G. E. Friederich, and the IronEx Group. 1994. Surface Seawater Nitrate and Silicate Distributions During the Galapagos Iron Experiments as Determined by an Automated Mapping System. EOS, 75, 150.

Stanton, T., and the Ironex Group. 1994. The open ocean iron enrichment experiment: Physical evolution of the iron enriched patch. EOS, 75, 134.

Watson, A., and the Ironex Group. 1994. Evolution of the geochemical signal during the open ocean iron fertilization experiment. EOS, 75, 135.

number of undergraduate students 0

number of graduate students 1

number of post-docs 0

other tech personnel 3

number of female graduate students 0

number of minority graduate students 0

number of asian graduate students 0

Deep-Sea Research, John Martin Special Issue, Proposed Submissions

Coale, K. H., Fitzwater, S., Blain, S., Coley, T., Hunter, C., K. Johnson, Stanton T., and Watson, A. The design and implementation of a mesoscale iron enrichment experiment in the Equatorial Pacific.

Coale, K. H., Tanner, S., Fitzwater, S. and Hunter, C., Buck, K. and Chavez, F? Phytoplankton species composition and biomass: The partitioning of POC and DOC during the IronEx and PlumEx experiments.

Gordon, M., Coale, K. H. and Johnson, K. S. Trace metal distributions and partitioning during the IronEx and PlumEx experiments in the Equatorial Pacific.

Hoge, F., et al. Distinct Fluorescence Signatures of an Iron-Enriched Phytoplankton Community in the Eastern Equatorial Pacific Ocean.

Hoge, F., et al. Bio-Optics survey of the Galapagos Islands Margins. Airborne chlorophyll, phycoerythrin and DOM fluorescence, upwelled radiance, downwelling irradiance, SST and AXBT profiles.

Kolber, Z., Greene, R., Falkowski, P., et al. Dynamics of photosynthetic response to iron fertilization in the equatorial Pacific.

Greene, R., Kolber, Z., Falkowski, P., et al. Biophysical response of marine phytoplankton to natural iron enrichment as measured by FRR (Fast Repetition Rate) Fluorescence: The PlumEx experiment.

Friederich, G. E., Sakamoto, C. M. and Millero, F. Surface seawater distributions of inorganic carbon and nutrients within the Galapagos Plume: Results from the PlumEx experiments using automated chemical mapping.

Stanton, T., et al, Watson, A. et al. The open ocean iron enrichment experiment: Physical evolution of the iron enriched patch.

Watson, A., et al, Millero, F. et al. Evolution of the geochemical signal during the open ocean iron fertilization experiment.

Barber, R., S. Lindley, R. Bidigare, M. Latasa, M. Ondrusek, K. Buck, F. Chavez, S. Chisholm, K. Coale, K. Johnson, S. Tanner, A. Watson, C. Law, K. Van Scoy and M. J. Liddicoat. The In Situ Phytoplankton Response to Natural and Experimental Iron Enrichment.

Lindly S. et al., Changes in the quantum yield of photosynthesis in phytoplankton during the IronEx and PlumEx experiments.

Chisholm et al. The Picoplankton response to iron addition (Plume and Patch and Bottles).

Chisholm et al. The changes in phytoplankton community size structure (flow cytometrically derived and size-fractioned chlorophyll) in iron addition (Plume and Patch and Bottles).

Turner, S. M., Malin, G., Hatton. and Liss, P. S. Iron Fertilization: Effects on dimethyl sulfide and dimethylsulphoniopropionate production.

Nightingale, P. D., Turner, S. M. Malin, G. and Liss, P. S. Iron fertilization: Effects on production of biogenic halocarbons in seawater.

Ondrusek, M., Latasa, M. M., Bidigare, R. Pigment composition and community structure in the IronEx and PlumEx experiments.

Tindale, N. and Seymour, J., and ....? Composition, concentration and chemical fluxes

of atmospheric aerosols during PlumEx. Results of single particle analysis.

Collins, C., Steger, J. and G. Montenegro. Upper ocean circulation during the Galapagos Plume experiment: Implications for source waters and mixing.

Chavez, F. et al. Continental shelves, iron fertilization and the structure of phytoplankton communities.

Lewis, M. R. et al., Bio-optical characteristics of the IronEx experiment and beyond: Results from the optical buoys that would not die. (or: The optical energizer bunny explores the Pacific).